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SOURCES OF DISSOLVED SOLIDS IN THE UPPER COLORADO RIVER BASIN

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Abstract

The total dissolved solids (TDS) discharge and concentration (salinity) in the Colorado River are a major concern to agricultural, municipal, and industrial water users in both the United States and Mexico. Most of the TDS load in the Colorado River originates in the Upper Basin above Lees Ferry, Arizona. Several studies have estimated various components of the annual TDS discharge in the Upper Basin. Some studies have estimated the annual TDS discharge that would have occurred had there been no water resources development (natural component), while others have estimated the amount of dissolved solids contributed by ground water. The present study uses data from these previous studies, and expands on their work by estimating the amount of dissolved solids contributed by upland or surface sources. The results indicate that the annual yield from surface sources of dissolved solids varies considerably in the Upper Basin. Annual yields can be as low as 0.002 tons per acre (t/a), or 1.3 tons per square mile (t/mi^2) for headwaters areas with little or no saline soils and geology to 0.029 t/a, or 18.6 t/mi^2 for a basin with a high percentage of saline soils. The highest yield of 0.036 t/a, or 23 t/mi^2 occurs in a basin that may be heavily influenced by coal-resource development. The average yield of about 0.022 (t/a), or 14 (t/mi^2) accounts for about 17 percent of the TDS discharge at Lees Ferry.

Annual surface yield values increase as drainage area decreases and percentage of saline soils increase. The annual surface yield value for the Price River Basin is about 0.029 t/a (18.3 t/mi^2), ephemeral streams in Wyoming were found to have a value of about 0.04 t/a (25.6 t/mi^2), and the value for small upland areas can be as high as 0.08 t/a. Ground water is the dominate source of dissolved solids in the Upper Basin accounting for about 43 percent of the TDS discharge at Lees Ferry. The combination of surface and ground water contributions (natural componant) accounts for about 60 percent of the TDS discharge at Lees Ferry. The remaining 40 percent is due to anthropogenic sources, mostly irrigation. Corresponding concentrations show that the natural concentration is less than about 300 mg/l and the surface runoff concentration is less than 130 mg/l.

Introduction

Description of the TDS Problem

The Colorado River and its tributaries provide municipal and industrial water to about 27 million people and irrigation water to nearly 4 million acres of land in the United States (U.S. Bureau of Reclamation, 2001). The river also serves about 2.3 million people and 500,000 acres in Mexico (U.S. Bureau of Reclamation, 2001). The (TDS) concentration (salinity) of the Colorado River is a major concern in both the United States and Mexico. Salinity affects agricultural, municipal, and industrial water users. Damages in Mexico are unquantified, but damages in the United States are presently about $330 million per year (U.S. Bureau of Reclamation, 2001). Specific effects of dissolved solids on different water uses are discussed in U.S. Bureau of Reclamation, (2001). The Colorado River Basin Salinity Control Program is designed to reduce salt loading, primarily from Upper Basin sources. A knowledge of the contribution of TDS from various sources in the Upper Basin is necessary to appropriately direct control efforts.

Previous Studies of TDS Sources

Iorns et al., (1965) produced a comprehensive report on the water resources of the Upper Colorado River Basin including computations of TDS loads at gaging stations and some estimates of the natural component of those loads. The natural load at a specific location is defined as the TDS load that would have occurred if there had been no water-resources development upstream of that location (Mueller and Osen, 1988). The natural load can be subdivided into contributions from ground water and from surface runoff. Iorns et al., (1965) contains some estimates of the ground-water contribution, but the majority if these estimates are for small sub-basins. Iorns et al., (1965) divided the TDS load at Lees Ferry into a human component (40%) and a natural component (60%).

The U.S. Environmental Protection Agency (EPA), (1971) analyzed the salinity problem in the Colorado River and estimated percent contributions from various sources. The EPA (1971) differentiated the natural category into natural diffuse sources and natural point sources, but did not differentiate natural into ground water and surface contributions. For the upper basin above Lees Ferry, AZ, the percentages are natural diffuse sources 52 percent, natural point sources 6 percent, irrigation 41 percent, and municipal and industrial (M&I) 1 percent (U.S. Environmental Protection Agency 1971). Combining the natural diffuse and natural point source categories gives an estimate of 58 percent for all natural sources.

The Bureau of Land Management (Bentley et al., 1978) estimated the annual contribution of dissolved solids from public land in Colorado, Utah, and Wyoming. Bentley et al. (1978) also includes TDS loads at gaging stations in the Upper Colorado River Basin. The Bureau of Land Management and the U.S. Geological Survey (Bentley et al., 1980, and Warner et al., 1985) estimated the natural and ground-water contributions to the TDS load of the Upper Basin above the confluence of the Colorado and Green Rivers.

Bentley et al., (1980) were the first to attempt differentiating the natural load into surface and ground water components for the Upper Basin. Bentley et al., (1980) ranked the major sources of TDS loading in the Upper Basin above the confluence of the Colorado and Green Rivers into surface runoff (20%), ground water (38%) irrigation (41%), and M&I (1%). Bentley et al., (1980) arrived at their surface runoff estimate by using the computed surface yield from Bentley et al., (1978) of 697,900 tons from 27,357,000 acres of public land in Colorado, Utah and Wyoming. The 697,900 tons accounts for about 8 percent of the TDS load for the Upper Basin (Bentley et al., 1980). Bentley et al., (1980) then assumed that surface runoff from lands similar to those analyzed by Bentley et al., (1978) would account for another 7 percent of the total and that surface runoff from forested land would account for another 5 percent. Unfortunately Bentley et al., (1978) used incorrect acres for highly, moderate, and slightly saline soils for their yield of 697,900 tons. When the correct acreages are used the yield from public land in the Upper Basin reduces to 547,000 tons, which is about 6.3 percent of the TDS load for the Upper Basin. This revised value would substantially reduce the Bentley et al., (1980) estimate of surface yield for the Upper Basin.

In 1988 the U.S. Geological Survey (Mueller and Osen, 1988) estimated the natural dissolved solids discharge at gaging station locations in the Upper Colorado River Basin. Mueller and Osen, (1988) based their analysis on Iorns et al., (1965) but did not estimate ground water and surface contributions to the natural discharge. Mueller and Osen, (1988) also included revised computations of the TDS discharge at the gaging station locations. The U.S. Geological Survey (Vaill and Butler, 1999) analyzed TDS trends at gaging stations in the Upper Colorado River Basin. Vaill and Butler (1999) include computed TDS loads.

Differences in Geographic Extent

The Colorado River Compact of 1922 established a division point on the River to separate the Basin into a Lower and Upper Basin for legal, political, institutional, and hydrologic purposes (EPA, 1971). The dividing point is located one mile downstream from the mouth of the Paria River and two miles downstream from the gaging station at Lees Ferry, Arizona (Mueller and Osen, 1988). All of the publications discussed in this section, with the exception of EPA (1971), deal with some portion of the Upper Colorado River Basin. EPA (1971) deals with the entire Basin. Iorns et al., (1965) deals with the Upper Basin as it is legally defined (112,000 mi^2). Mueller and Osen, (1988) deals with the Basin upstream from the gage at Lees Ferry (111,800 mi^2), with upstream most stations of Colorado River near Glenwood Springs, CO (4,560 mi^2) , and Green River below Fontenelle Reservoir, WY (4,280 mi^2). Vaill and Butler (1999) deals with the Basin upstream from Lake Powell at Hite, UT (72,340 mi^2) with upstream most stations of Colorado River at Hot Sulphur Springs, CO (825 mi^2) and Green River near La Barge, WY (3,910 mi^2). Bentley et al. (1980), and Warner et al. (1985) deal with the Basin upstream of the confluence with the Green River (about 71,000 mi^2), with upstream most stations of Colorado River below Lake Granby, CO (312 mi^2) and Green River at Warren Bridge near Daniel, WY (468 mi^2). Bentley et al. (1978) deals with public land in the Upper Basin states of Colorado, Utah, and Wyoming (about 42,750 mi^2).

These inconsistencies in geographic extent limit the comparisons that can be done among the various studies to stations or areas in common. For this study the downstream most stations are Colorado River near Cisco, UT (24,100 mi^2), Green River at Green River, UT (44,850 mi^2), and San Rafael River near Green River, UT (1,628 mi^2). The combined drainage area of these three stations accounts for 59 percent of the Upper Basin as legally defined, and 92 percent of the Upper Basin above Lake Powell. The upstream most stations used in this study are Colorado River at Hot Sulphur Springs, CO, and Green River below Fontenelle Reservoir, WY. The drainage areas for stations at and below Green River near Green River WY include 4,260 mi^2 that are non-contributing (Mueller and Osen, 1988).

Purpose and Scope

The purpose of this study is to analyze the results of dissolved solids studies in the Upper Colorado River Basin and estimate the amount of dissolved solids being contributed by upland or surface sources. The study is primarily focused on major (>800 square miles) drainage areas in the Upper Colorado River Basin where the total, natural, and ground-water dissolved solids components have been computed or estimated. Some analyses from smaller areas are used for comparison.

Total Dissolved Solids

Iorns et al., (1965), Bentley et al. (1978), Mueller and Osen, (1988), and Vaill and Butler (1999) all include computed values for total dissolved solids discharge at various gaging stations in the Upper Basin (table 1). The TDS load at a gaging station is computed in one of two ways. The first is from a relation between the continuous record of water discharge and individual TDS analyses from periodic samples, and the second is from a relation between the electrical conductance of the water, which is measured continuously, and individual TDS analyses from periodic samples (Lieberman et al., 1987). Use of the second method is preferable and often improves the estimate of the dissolved solids load (Butler, 1996). Table 2 shows the mean, standard deviation, and coefficient of variation for the values in table 1. Generally the coefficient of variation shows good agreement among the TDS estimates. The mean values in table 2 are used for the analysis in this paper.

TABLES 1 AND 2 NEAR HERE

The Natural Component of Total Dissolved Solids

Iorns et al., (1965), and Mueller and Osen, (1988) estimated the natural component of the total dissolved solids discharge at various gaging stations in the Upper Basin (table 3). The agreement between values for stations contained in both studies is expected because Mueller and Osen, (1988) updated and adjusted the values presented by Iorns et al., (1965). Mueller and Osen, (1988) also used a weighted least-squares regression technique to model TDS discharge as a function of streamflow and several variables representing water resources development. When the model was calibrated for an individual site the development variables were set to zero to yield a relation between dissolved solids and discharge for conditions of no upstream development.

Table 3 shows the estimates of the natural component and the percent of total. For gaging stations on the Green and Colorado Rivers the natural component represents between 53 and 62 percent of the total dissolved solids discharge.

TABLE 3 NEAR HERE

Ground-Water Contributions to Total Dissolved Solids

Dissolved solids contributions from ground water, saline springs and seeps, and interflow through saline soils are collectively referred to as the ground-water contribution which is included in the natural category. Iorns et al., (1965), Bentley et al. (1980), and Warner et al. (1985) all attempted to estimate the ground water contribution to the dissolved solids discharge. Analyses by Iorns et al., (1965), are for mostly for small drainage basins and are not considered here. Analyses by Bentley et al. (1980), and Warner et al. (1985) were actually part of the same study. Warner et al. (1985) describe their approach as follows.

Discharge and water-quality data were collected at 142 sites in the Upper Colorado River Basin upstream from the confluence of the Colorado and Green Rivers in December 1977 and January 1978. A one-time sampling program was conducted. The assumption was made that the ground-water discharge from aquifers remains nearly constant during the year and also from year to year. That is, the variation of the ground-water discharge to streams during the year is assumed to be minimal, but no calculation was made to verify this. The year-to-year variation of ground-water discharge to the streams was evaluated by comparing base-flow hydrographs from gaging stations with data collected during this study. In general, the variation was no more than 20 percent. The data were collected in this study following an abnormally dry year; thus, the calculated salinity contributed to the streamflow by ground water may be smaller than the long-term average.

Calculations of the salt-load contributions to streams by major springs were made by directly measuring the spring discharges and indirectly by evaluating the chemical quality of the water. In some places the springs flow directly into the stream channel and direct measurement of the discharge is not possible. In these situations, measurements of the salinity of the river upstream and downstream from the spring, the salinity of the spring itself, and a measurement of the discharge of the river were used to compute the approximate spring discharge to the river. It was assumed that the river discharge was much greater than the spring discharge, and, therefore, the streamflow upstream and downstream from the spring discharge was assumed constant.

With respect to the comment that the data were collected following an abnormally dry year, it is worth noting that Iorns et al., (1965) used a flow-duration curve separation technique to compute the ground-water contribution. A comparison of the seven stations that are common to both studies shows that the Iorns et al., (1965) estimate exceeds the Warner et al., (1985) estimate by at least a factor of 1.72 for five of the stations. This comparison does not prove that estimates of Warner et al., (1985) are low, but it does suggest that the possibility should not be discounted.

Bentley et al. (1980) provides some adjustments to the Warner et al. (1985) values to correct for contributions from irrigation return flow water (Bentley et al. (1980), were able to publish 5 years ahead of Warner et al. (1985), due to differences in agency publication procedures.). These adjustments were based on water-quality data collected from irrigation drainage channels in the Lower Gunnison and Grand Valley areas. Table 4 shows the results of the ground water estimates. The ground water component accounts for over 50 percent of the natural component, and can account for over 90 percent of the natural component.

TABLE 4 NEAR HERE

Other Studies of the Ground-Water Contribution

The reach of the Colorado River between the towns of Dotsero and Glenwood Springs, CO represents the largest single source of dissolved solids in the Upper Colorado River Basin (Liebermann et al., 1989). About 500,000 tons/year of salt enter the Colorado River in this reach through thermal springs and direct ground water inflow (Liebermann et al., 1989, Warner et al., 1985, Iorns et al., 1965). The TDS concentration in the ground water comes from dissolution of halite and gypsum within the Pennsylvanian Eagle Valley Evaporite (Kirkham et al., 1999, Chafin and Butler, in press). The total annual contribution from dissolution of the Eagle Valley Evaporite is estimated to be 901,000 tons (Chafin and Butler, in press). This contribution alone accounts for about 60 percent of the TDS load at Cameo, CO (Chafin and Butler, in press).

The Green River basin is the largest tributary basin to the Colorado River above Lees Ferry. DeLong (1977) found that 88 percent of the annual salt load gain in the Green River between gages below Fontenelle Reservoir and near Green River, WY is due to ground-water inflow. The difference in TDS discharge between these two stations, using the data in Table 1, is 163,976. Eighty eight percent of this difference is 144,291. Adding 144,291 to the ground water component below Fontenelle (131,000) gives 275,291, which is slightly larger than the Warner et al. (1985) estimate of 259,000 for the Green River near Green River, WY. Table 4 shows that the ground-water component accounts for between 59 and 83 percent of the natural component for stations on the Green River.

The Price River Basin has been the subject of several studies. Duffy et al., (1985) state that "Through a literature review and supplemental field studies, CH2M Hill (1983) estimated that as much as 90 percent of the stream (Price River) salinity originates in ground water flowing through salt bearing strata." This estimate agrees with estimates of the surface water contribution. Estimates of the percentage of annual salt load at Price River at Woodside UT (241,000 tons per year) that comes from surface sources range from <5% (Riley et al., 1982a) to 12% (Dixon, 1978). In another study of the Price River Basin, Bowles et al., (1982) concluded that surface salt sources produce a relatively small fraction of the total loading.

Riley et al., (1982b) also found that high salinity levels in intermittent streams during the snowmelt period suggests that much of the salt pickup occurs not as a result of overland flow but from water that percolates downward through the Mancos Shales and then moves more or less laterally as interflow to the intermittent channels.

In discussing the annual mean dissolved-solids load from the Grand Valley, Butler (1996) states that the BOR (1986) estimated that at least 95 percent of the load was from was from shallow ground-water sources.

Surface-Water Contributions to Total Dissolved Solids

The surface-water contribution to the total dissolved solids discharge is computed by subtracting the ground-water contribution from the natural component. Table 5 lists all previous components and shows the estimates for the surface component. Table 6 shows the corresponding annual yield in tons per acre.

TABLES 5 AND 6 NEAR HERE

Table 6 also contains data for Price River at Woodside, UT. Unitex Corporation (1982) used data from 30 major summer and fall convective storms, excluding baseflows, to estimate that surface runoff accounted for 11.2% of the total salt load passing the Price River at Woodside gage. The 11.2 percent estimate is on the high end of the range from <5% (Riley et al., 1982a) to 12% (Dixon, 1978) for the surface component at Price River at Woodside. This range was established through the use of models. The yield value of 0.029 t/a is the second highest in table 6, but this is not unexpected due to the unique nature of the Price River Basin. According to Jeppson et al. (1968) the Price River contribution to the Colorado River flow measured at Lees Ferry is only 0.66 percent, while the salt contribution is 2.79 percent. No other major tributary in the upper basin has such a high salt to water ratio as the Price River (Riley et al., 1982b).

The lowest yield value of 0.002 t/a for the Colorado River at Hot Sulphur Springs is also an expected result. Data from the gage at Hot Sulphur Springs represents the upper 825 square miles of the basin upstream of saline soils and geology. Another low value of 0.006 t/a for the Green River near Green River WY may reflect an underestimation of the natural component, perhaps due to the large contribution of ground water between this location and the upstream gage near Fontenelle Reservoir (DeLong, 1977). The low value of 0.003 t/a for the Duchesne River near Randlett, UT, and the high value of 0.036 for the Yampa River near Maybell, CO are also suspect. The Duchesne River near Randlett, UT has the highest coefficient of variation in table 2, is tied for the lowest percentage of total due to natural in table 3 and has the highest percentage of natural due to ground water in table 4. Mueller and Osen, (1988) state various reasons for suspecting that their results for the Duchesne River near Randlett, UT are inaccurate. The natural component for the Duchesne River near Randlett, UT may be underestimated.

The high value of 0.036 for the Yampa River near Maybell is higher than the value for the Price River at Woodside and is equivalent to yield values (0.040) for ephemeral streams in WY (DeLong and Wells, 1988). A possible explanation for this high value might be related to the influence of energy development activities. Vaill and Butler (1999) state that the major land-use change in the Yampa Basin upstream from Maybell has been the expansion of coal-resource development since the early 1960's. Vaill and Butler (1999) go on to say that Lieberman et al., (1989) cite several references that might indicate the upward trends in dissolved-solids concentrations and loads could be attributed to spoil piles and the associated runoff. For example, Lieberman et al., (1989) sate that runoff from spoil piles in the Yampa River Basin produces three to six times the runoff from undisturbed land, and springs have been observed at the toe of spoils, changing intermittent streams to perennial streams. While the low values for the Duschesne and the Green near Green River, WY may be suspect, the high value for